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Control of Remotely Guided Vehicles: A Method for Approaching a Stationary Contact at a Particular Arrival Angle or for Tail-Chasing a Moving Contact

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PREFACE

This report was prepared under NUWC Division Newport's Bid and Proposal (B&P) program. The B&P program provides funding for the preliminary, conceptual, and technical work required to generate complete and comprehensive proposals for direct-funded work. Principal investigators were Anthony F. Bessacini and Robert F. Pinkos (Code 2213).

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13. ABSTRACT *(Maximum 200 words)*

This report describes a method for the automatic control of a vehicle when the goal is to approach a stationary target at a particular angle or perform a tail chase on a moving target. This method can be used for controlling a remotely guided vehicle, such as a torpedo, mine, or missile, from a stationary or moving platform, such as a submarine. Because it avoids the high, often unattainable turning rates required of the pursuer, the trajectory developed by this controller is a significant improvement over that obtained from classical pursuit trajectory.

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LIST OF ABBREVIATIONS AND ACRONYMS

CCS	Combat control system
CO	Commanding officer
CMS	Contact management subsystem
NUWC	Naval Undersea Warfare Center
SCCS	Submarine combat control system
WMS	Weapon management subsystem

CONTROL OF REMOTELY GUIDED VEHICLES: A METHOD FOR APPROACHING A STATIONARY CONTACT AT A PARTICULAR ARRIVAL ANGLE OR FOR TAIL-CHASING A MOVING CONTACT

1. INTRODUCTION

Submarine combat control systems (SCCSs) are responsible for the employment of various underwater vehicles (e.g., torpedoes, mines, missiles). One of the vehicles commonly deployed is an acoustic homing torpedo, an extremely complex and costly vehicle. Survivability and cost dictate that this vehicle be employed in the most effective manner.

There are two major phases associated with the employment of a submarine-launched torpedo; these are referred to as "prelaunch" and "postlaunch" employment. During the prelaunch phase, the SCCS uses real-time, *in-situ* measured information on the contact/target and the environment with computer-stored data to determine the weapon prelaunch settings that will result in maximum weapon effectiveness. During the postlaunch guidance phase, the submarine continues to obtain real-time sensor measurements. The weapon parameters are updated with information as a function of the ongoing tactical situation via a remote link to the weapon control portion of the combat control system (CCS).

One of the primary postlaunch considerations is the selection of the trajectory that the vehicle will follow during its delivery/search phase. Control laws presently being used in the SCCS include corrected intercept, bearing rider, and pursuit. This report describes a new controller, termed "tail-chase," for weapon trajectory control.

As the name implies, the tail-chase trajectory results in the vehicle always attacking the contact from the rear/tail. The importance of this trajectory is clear when the amount of noise generated by the submarine propellers and the amount/type of damage that can be inflicted when a submarine is hit in this vicinity are considered. The tail-chase trajectory allows the craft to be disabled using a less lethal weapon. Although a classical pursuit controller can result in a tail-chase trajectory, depending on the geometry and speed ratio of the torpedo to contact, the turn rates required by the torpedo can be prohibitively large (i.e., unattainable).

The tail-chase controller described in this report uses a new control variable along with a heuristic rule set to overcome the high turning rate limitation. In addition, the approach trajectories avoid masking the contact signal after launch and allow the vehicle to approach the contact at a deceptive angle; i.e., an angle that makes it difficult for the contact to determine vehicle launcher position. Another feature of the new tail-chase controller is its ability to deliver a vehicle to a stationary target/position (e.g., to place a mine at a particular location) at any desired angle.

2. BACKGROUND

Figure 1(a) is a block diagram that illustrates some of the important elements of a submarine combat system. Central to this system is the combat *control* system, which assists the commanding officer (CO) in decision-making for the platform. The sophisticated architecture of the CCS includes high-powered computers and displays that use sensor and other input data to perform the complex computations necessary to provide a real-time tactical picture and viable operational alternatives for any desired mission.

The weapon management subsystem (WMS), shown in figure 1(b), is a component of the CCS and is responsible for determining the parameters/orders sent to the launched vehicle in both the prelaunch and postlaunch phases. This subsystem uses contact and own ship navigation sensor data, provided by the contact management subsystem (CMS), and other inputs (such as environmental information) in order to determine and transmit the optimum settings for the vehicle being employed. Figure 1(c) depicts the postlaunch section of the WMS, which deals with the determination of those commands issued after vehicle launch. The trajectory control portion of the WMS is responsible for the computation and transmission of the command parameters the vehicle requires to maintain the selected trajectory/path.

Typical weapon trajectories are intercept, bearing rider, and pursuit. This report addresses a new controller, which is implemented using fuzzy control methodology.

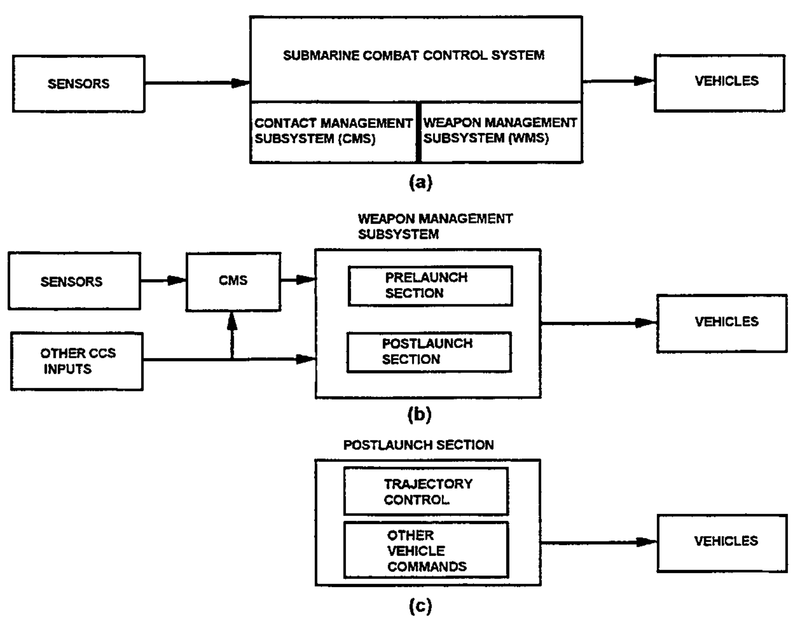


Figure 1. High-Level Block Diagrams: (a) Submarine Combat Control System, (b) Weapon Management Subsystem, and (c) Postlaunch Section

3. METHODOLOGY

SYSTEM DESCRIPTION

This report deals with the problem of guiding an underwater vehicle on a tail-chase trajectory against a moving contact or on a trajectory that allows for intercept of a stationary contact/position at any specified angle. As in previous work (references 1-4), which dealt with other vehicle trajectories (intercept and bearing rider), the system devised uses fuzzy set theory to implement a controller that continuously determines the postlaunch commands to be sent over the communication link to the vehicle being guided. Using contact bearing, range, and course estimates provided by the CMS and vehicle data from the vehicle model, the trajectory model subsystem determines the necessary input data for the fuzzy subsystem. The fuzzy subsystem processes the inputs and determines the desired vehicle trajectory commands. The resultant commands are sent over the communication link to the vehicle and are also sent to update the vehicle model.

PROBLEM GEOMETRY AND BLOCK DIAGRAM

The problem geometry is depicted in figure 2. In classical pursuit guidance schemes, which end in a tail chase, the controller is typically concerned with reducing the angle β to zero. The problem with this approach is that, depending on the geometry and the contact and vehicle speeds, the turning rate required of the vehicle can be prohibitive. The control method presented in this report uses the angle β, but also introduces a new control variable α, defined in figure 2.

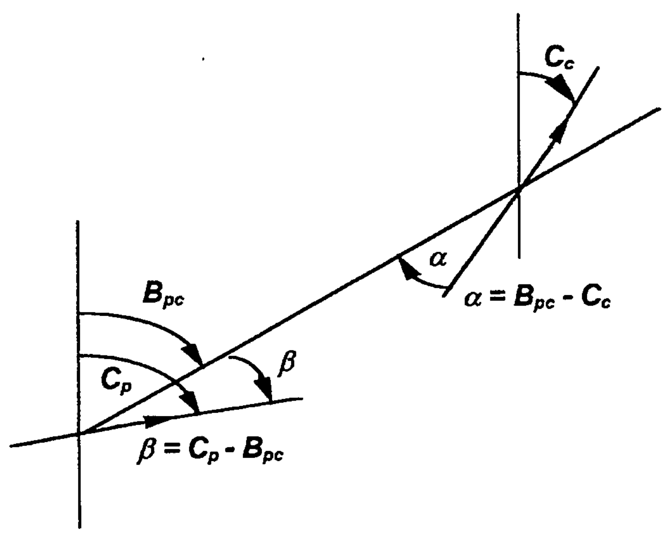


Figure 2. Problem Geometry

The introduction of this new control variable and the set of heuristic rules employed result in an entirely new trajectory. This trajectory results in a tail chase of the contact, but does not require the high turning rates of the classical pursuit controller. Further, with the standard pursuit trajectory, there can be a problem of continuing to track the contact after the vehicle is launched because the vehicle is too close to the line of sight from the launching platform to contact. The new trajectory minimizes this problem.

Figure 3 is a block diagram of the postlaunch control guidance system containing the fuzzy controller. The system comprises the sensor subsystem, the CMS, the trajectory model subsystem, the vehicle subsystem, and the fuzzy control subsystem. The functional components that make up the major portion of the fuzzy control system would be implemented in the computer/display portion of any SCCS.

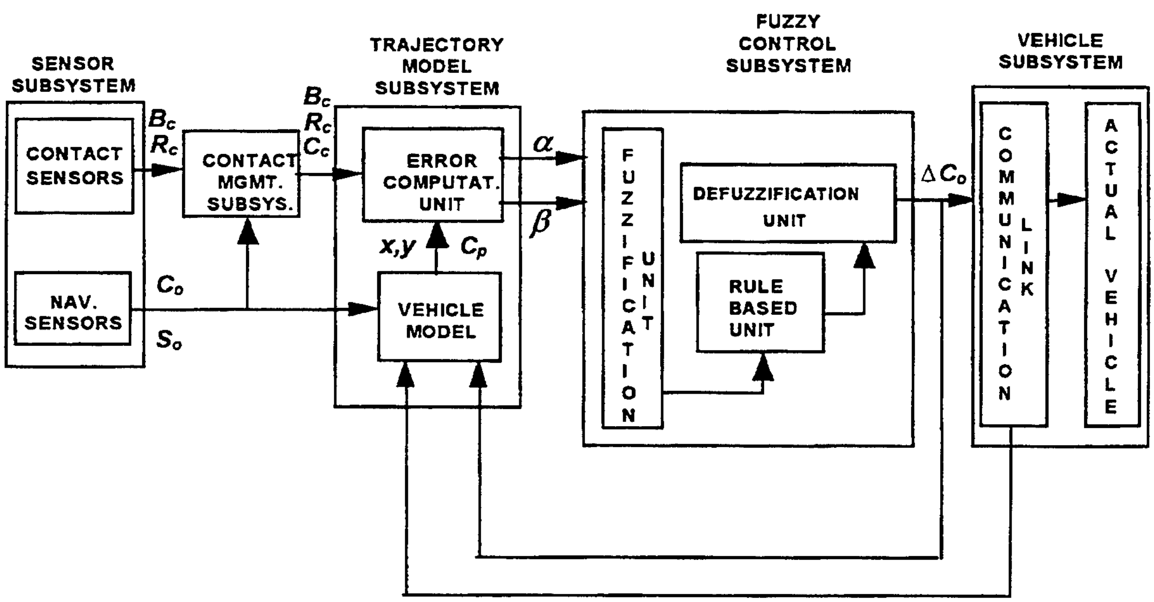


Figure 3. Block Diagram of the Tail-Chase Control System

Sensor Subsystem

The sonar sensors aboard the underwater firing vessel provide measurements of parameters associated with the contact of interest. For the purpose of this report, these parameters are considered to be measured bearing and range.

The navigation sensors measure the firing vessel parameters of heading (C_o) and speed (S_o). These parameters are required to determine the postlaunch position of the vessel relative to the firing point.

Contact Management Subsystem

The CMS uses contact sensor data and navigation sensor data to provide, among other things, estimates of the contact state vector (contact bearing, contact range, contact course, contact speed).

Trajectory Model Subsystem

The trajectory model subsystem comprises the error computational unit and the vehicle model. Although these units are currently part of the SCCS, they do not deal with the new control error variables identified in this report.

The error computational unit must process data from the CMS and from the vehicle model to determine the necessary inputs for the fuzzy control subsystem. These inputs consist of (1) the angle defined as the difference between the bearing from the vehicle to the contact and the contact course, and (2) the angle between the vehicle course and the bearing from the vehicle to the contact.

The vehicle model is a detailed mathematical model that simulates the dynamic and logical behavior of the vehicle to provide estimates of both vehicle kinematics (course (C_p), speed (S_p), and position (X_p, Y_p, Z_p)) and state (e.g., search). This model processes data fed back from the vehicle, vessel navigational sensor information, and vehicle commands. This processing is required by the firing vessel (from which the guidance commands are issued) to continuously compute the bearing from the vehicle to the contact.

Vehicle Subsystem

A wire link supports two-way communication between the firing vessel and the underwater vehicle. A variety of commands can be sent from the vessel to the vehicle to modify the vehicle state. These commands can be categorized as those that affect safety, modify acoustic sensor settings, and impact the kinematic/dynamic behavior of the vehicle. This report is concerned with those commands that influence the vehicle postlaunch trajectory.

The vehicle uses the commands sent over the wire communication link to update its trajectory to maintain a course that ultimately results in the intercept of the contact. The vehicle is continuously issued update trajectory commands at a periodic rate until the internal sensor system detects the contact and initiates homing (i.e., acquisition).

Fuzzy Control Subsystem

The fuzzy contol subsystem contains the units that use the newly defined variables as inputs and process them with the set of heuristic rules to obtain the changes in vehicle course required to achieve the desired tail-chase trajectory. Each of the functional units of the fuzzy control subsystem is described below.

Fuzzification Unit. The fuzzification unit takes crisp inputs and encodes them into fuzzy sets. The input variables associated with the system are the approach angular error $x1$ and the pursuit angular error $x2$ and are defined as

$$x1 = \alpha = B_{pc} - C_c,$$

$$x2 = \beta = C_p - B_{pc}.$$

Encoding of the system inputs requires mapping crisp numerical measurements into fuzzy set representations or linguistic variables. The universe of discourses for both the fuzzy input and output variables have been defined. The universe of discourses for inputs $x1$ and $x2$ are identical and are composed of the linguistic variables defined by the following term sets:

$$T(x1) = T(x2) = \left\{T_{xj}^1,\ T_{xj}^2,\ T_{xj}^3,\ T_{xj}^4,\ T_{xj}^5,\ T_{xj}^6,\ T_{xj}^7\right\} = (NL,\ NM,\ NS,\ ZE,\ PS,\ PM,\ PL),$$

where

$$j = 1, 2,$$

and

NL = negative large,
NM = negative medium,
NS = negative small,
ZE = zero,
PS = positive small,
PM = positive medium, and
PL = positive large.

Figure 4(a) depicts the identical sets of membership functions $\mu(x1)$, corresponding to input $x1$, and $\mu(x2)$, corresponding to input $x2$,

$$\mu(x1) = \mu(x2) = \left\{\mu_{xj}^1, \mu_{xj}^2, \mu_{xj}^3, \mu_{xj}^4, \mu_{xj}^5, \mu_{xj}^6, \mu_{xj}^7\right\},$$

where $j = 1, 2$. The membership functions are given by the following equations:

for $j = 1, 2$ and $i = 2, 3, 4, 5, 6$,

$$\mu_{xj}^i = 1 - \left(\left|xj - C_{xj}^i\right|\right) \big/ \delta_{xj}^i \qquad \text{for } C_{xj}^i - \delta_{xj}^i \le xj \le C_{xj}^i + \delta_{xj}^i,$$

$$\mu_{xj}^i = 0 \qquad \text{for } C_{xj}^i - \delta_{xj}^i > xj > C_{xj}^i + \delta_{xj}^i;$$

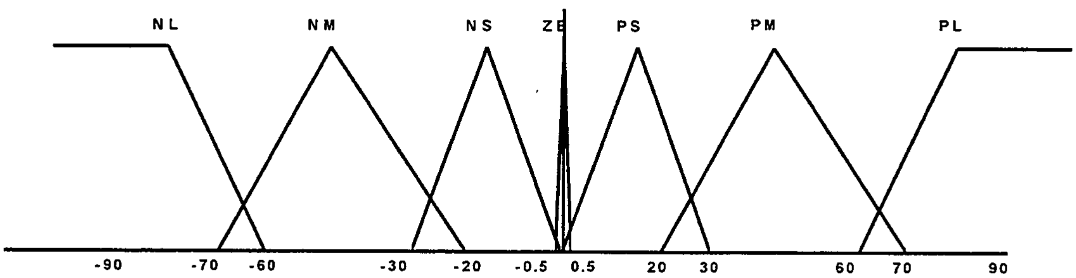
for $j = 1, 2$ and $i = 1, 7$,

$$\mu_{xj}^{i} = 1 - \left(\left|xj - C_{xj}^{i}\right|\right) / \delta_{xj}^{i} \qquad \text{for } a^{i}C_{xj}^{i} \geq a^{i}xj \geq a^{i}\left(C_{xj}^{i} - a^{i}\delta_{xj}^{i}\right),$$

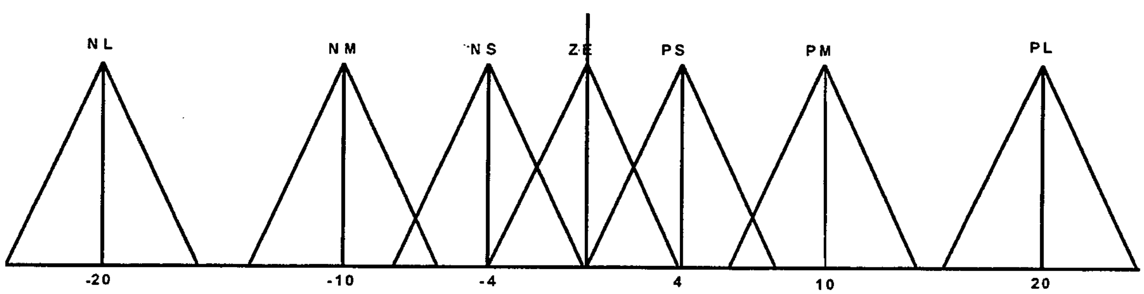
$$\mu_{xj}^{i} = 1 \qquad \text{for } a^{i}C_{xj}^{i} < a^{i}xj,$$

$$\mu_{xj}^{i} = 0 \qquad \text{for } a^{i}\left(C_{xj}^{i} - a^{i}\delta_{xj}^{i}\right) > a^{i}xj,$$

where $a^{i} = 1$, except for $i = 1$ where $a^{1} = -1$.



(a)



(b)

Figure 4. Universe of Discourses for (a) α ***and*** β, ***and (b)*** ΔC

The system output variable, or control variable, is the vehicle course command (ΔC), and the universe of discourse for ΔC is composed of the seven linguistic variables defined by the following term set:

$$T(\Delta C) = \left\{T_{\Delta C}^{1},\ T_{\Delta C}^{2},\ T_{\Delta C}^{3},\ T_{\Delta C}^{4},\ T_{\Delta C}^{5},\ T_{\Delta C}^{6},\ T_{\Delta C}^{7}\right\} = (NL,\ NM,\ NS,\ ZE,\ PS,\ PM,\ PL).$$

The set of membership functions $\mu(\Delta C)$ corresponding to output ΔC,

$$\mu(\Delta C) = \left\{ \mu_{\Delta C}^{1},\ \mu_{\Delta C}^{2},\ \mu_{\Delta C}^{3},\ \mu_{\Delta C}^{4},\ \mu_{\Delta C}^{5},\ \mu_{\Delta C}^{6},\ \mu_{\Delta C}^{7} \right\},$$

is depicted in figure 4(b) and given by the following equations:

for $i = 1, 2, 3, 4, 5, 6, 7,$

$$\mu_{\Delta C}^{i} = 1 - \left(\left| \Delta C - C_{\Delta C}^{i} \right| \right) / \delta_{\Delta C}^{i} \qquad \text{for } C_{\Delta C}^{i} - \delta_{\Delta C}^{i} \le \Delta C \le C_{\Delta C}^{i} + \delta_{\Delta C}^{i},$$

$$\mu_{\Delta C}^{i} = 0 \qquad \text{for } C_{\Delta C}^{i} - \delta_{\Delta C}^{i} > \Delta C > C_{\Delta C}^{i} + \delta_{\Delta C}^{i}.$$

The values of the membership constants C and δ are given in table 1.

Table 1. C and δ Constants

	$\mu(x1) = \mu(x2)$		$\mu(\Delta C)$	
i	$C_{x1,2}^{i}$	$\delta_{x1,2}^{i}$	$C_{\Delta C}^{i}$	$\delta_{\Delta C}^{i}$
1	-75	15	-20	4
2	-45	25	-10	4
3	-15	15	-4	4
4	0	0.5	0	4
5	15	15	4	4
6	45	25	10	4
7	75	15	20	4

Rule-Based Unit. The matrix in figure 5 defines the heuristic relationships that resulted from translating an understanding of torpedo guidance to a set of rules. Each entry in the matrix corresponds to a "rule" and defines the input/output relationships among the fuzzy variables. For example, the rule defined by the entry in the first row and first column of the matrix is:

IF α is NL AND β is PL, THEN ΔC is NL.

		α						
		NL	NM	NS	ZE	PS	PM	PL
	PL	NL	NL	NL	NL	NM	NM	NL
	PM	NL	NM	NM	NM	NM	PS	ZE
	PS	NM	NS	NS	NS	PS	PM	PM
β	ZE	NL	NL	NS	ZE	PS	PL	PL
	NS	NM	NM	NS	PS	PS	PS	PM
	NM	ZE	NS	PM	PM	PM	PM	PL
	NL	PL	PM	PM	PL	PL	PL	PL

Figure 5. Heuristic Rule Matrix

For each fuzzy rule that is fired, there is a fuzzy implication and an associated fuzzy implication function. The determination of the fuzzy implication functions is explained with an example in which two rules are fired:

(1) IF $x1$ is T_{x1}^{2} AND $x2$ is T_{x2}^{4} THEN ΔC is $T_{\Delta C}^{1}$,

(2) IF $x1$ is T_{x1}^{3} AND $x2$ is T_{x2}^{5} THEN ΔC is $T_{\Delta C}^{3}$.

The numerical strength of the output of rules 1 and 2 can be expressed respectively as

$$\zeta_{(1)} = y_{x1}^{2} \wedge y_{x2}^{4} = \min\left(y_{x1}^{2}, y_{x2}^{4}\right),$$

$$\zeta_{(2)} = y_{x1}^{3} \wedge y_{x2}^{5} = \min\left(y_{x1}^{3}, y_{x2}^{5}\right),$$

where y_{xj}^{i} is μ_{xj}^{i} evaluated at a specific value of *xj*(*t*) at time *t*, and $\wedge$ denotes fuzzy "and."

The inferred value of the control action from the first rule is $\zeta_{(1)}\,\mu_{\Delta C}^{1}(\Delta C)$. Similarly, the inferred value of the control output from the second rule is $\zeta_{(2)}\,\mu_{\Delta C}^{3}(\Delta C)$.

The output composite implication function ($\underline{\mu}_{\Delta C}(\Delta C)$) of the rule-based unit for this example is expressed as

$$\underline{\mu}_{\Delta C}(\Delta C) = \mu(\Delta C)_{(1)} \vee \mu(\Delta C)_{(2)} = \zeta_{(1)}\,\mu_{\Delta C}^{1}(\Delta C) + \zeta_{(2)}\,\mu_{\Delta C}^{3}(\Delta C),$$

where $\vee$ denotes the fuzzy "or."

The determination of the composite implication function for the example can, in general, be expressed as

$$\underline{\mu}_{\Delta C}(\Delta C) = \sum\nolimits_{k} \zeta_{(k)}\,\mu_{\Delta C(k)}(\Delta C),$$

where $\mu_{\Delta C(k)}(\Delta C)$ denotes the output membership function of the *k*-th rule fired, and $\sum_{k}$ indicates summation over all the rules fired.

Defuzzification Unit. The defuzzification unit takes the fuzzy outputs from the rule-based unit and decodes them into a crisp output that is acceptable for use in vehicle control. This unit employs a strategy that maps fuzzy control actions defined over an output universe of discourse (see figure 4(b)) into a space of crisp control actions (i.e., course commands). This application uses the centroid method of defuzzification,. The centroid of the composite function is used as the crisp control value and is computed as

$$\Delta C = \sum\nolimits_{k} \left\{ \left(\zeta_{(k)} C_{\Delta C(k)} \right) I_{\Delta C(k)} \right\} \Big/ \sum\nolimits_{k} \zeta_{(k)}\, I_{\Delta C(k)},$$

where $\sum_{k}$ indicates summation over all the rules fired, and $I_{\Delta C(k)}$ and $C_{\Delta C(k)}$ are defined as the respective area and centroid of the *k*-th rule consequent set membership function.

4. RESULTS/SAMPLE RUNS

The fuzzy controller described in section 3 was implemented using a real-time, high-fidelity laboratory simulation, and many runs were made. This section presents a sample of the results obtained for stationary and moving contacts.

ANGLE OF ARRIVAL AT A STATIONARY CONTACT/POSITION

Figure 6 depicts the geometry for the first and second sample runs. In the first scenario, it was desired to guide a vehicle to a stationary contact or position so that the vehicle arrived at an angle of 180° as measured from the north. In the second scenario, it was desired that the vehicle arrive at the contact position at an angle of 135°.

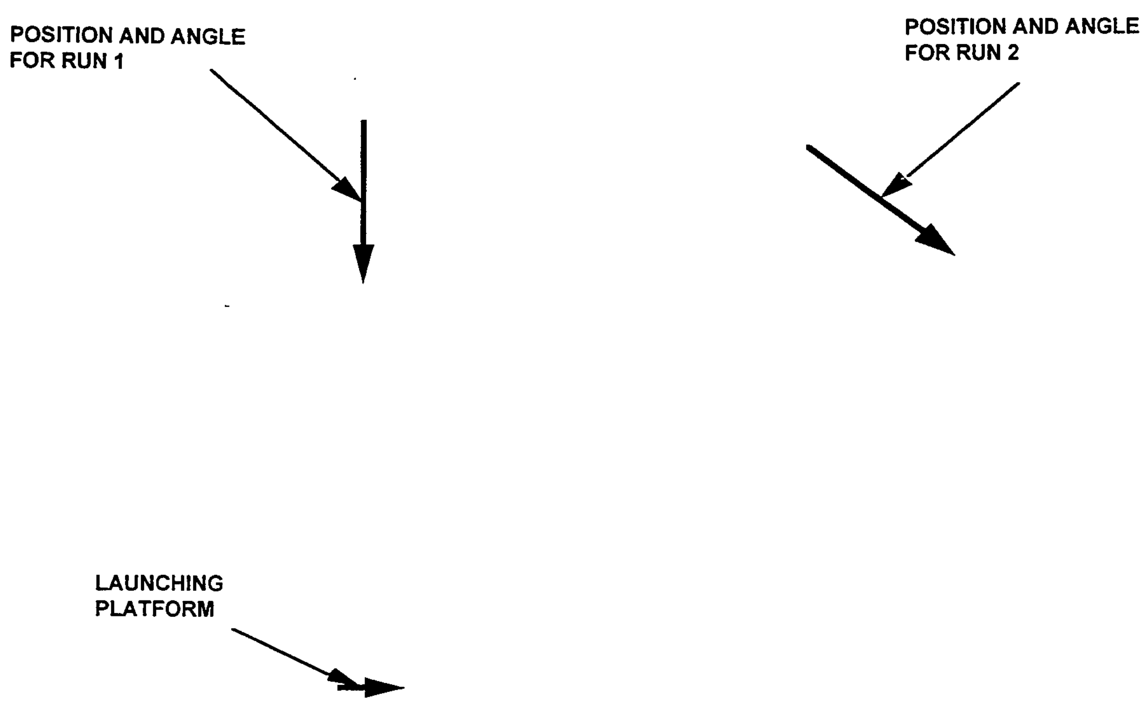


Figure 6. Geometry for Sample Runs 1 and 2

Figures 7 and 8 show the resulting respective trajectories when a classical pursuit controller of the type presently used in combat control applications was employed. As expected, the vehicle arrived at the desired positions at angles of 0° and 45°, respectively, because the standard pursuit controller does not use any contact angle information, but simply attempts to point the vehicle at the contact/position.

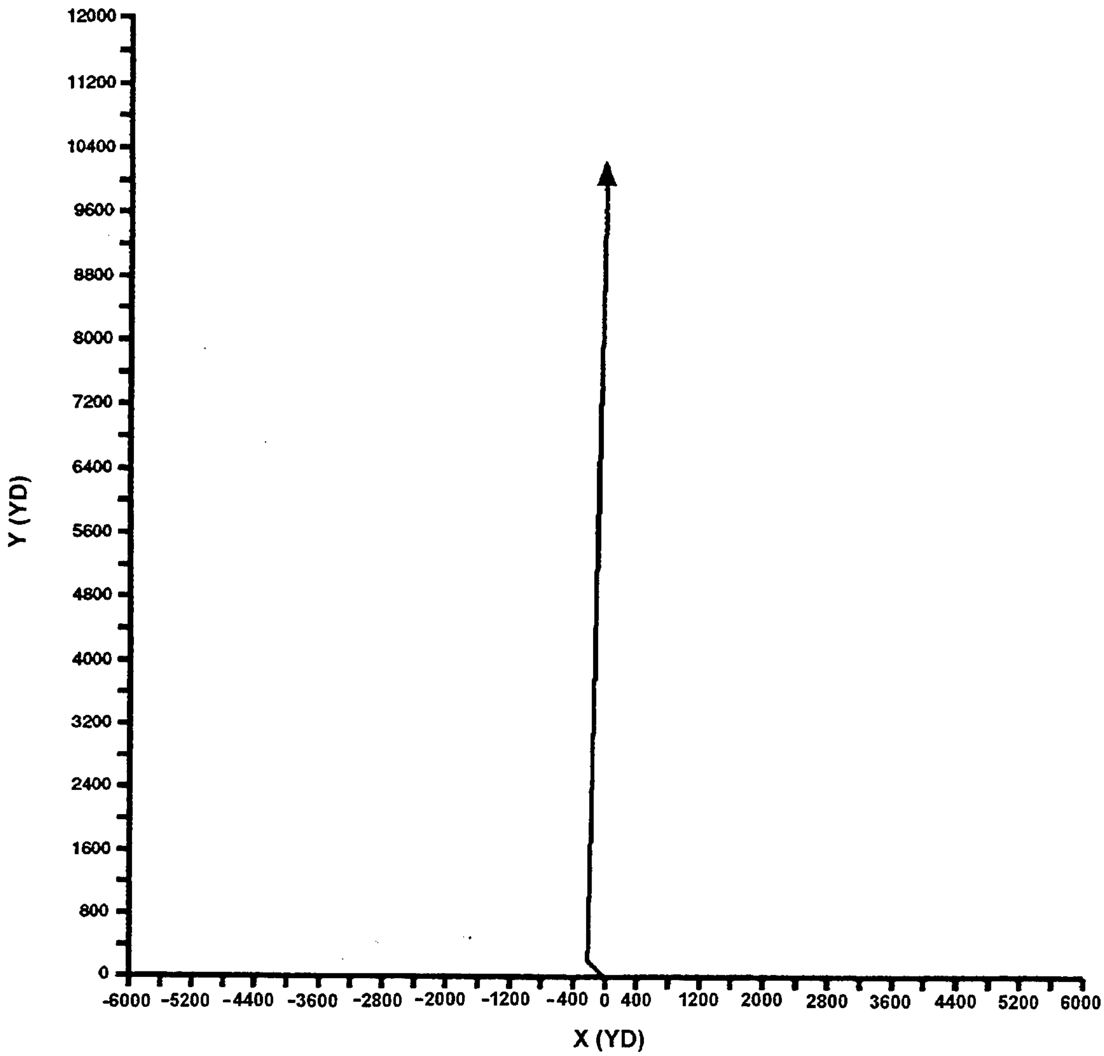


Figure 7. Pursuit Trajectory for Run 1: Approach Angle = 0° (Stationary Contact)

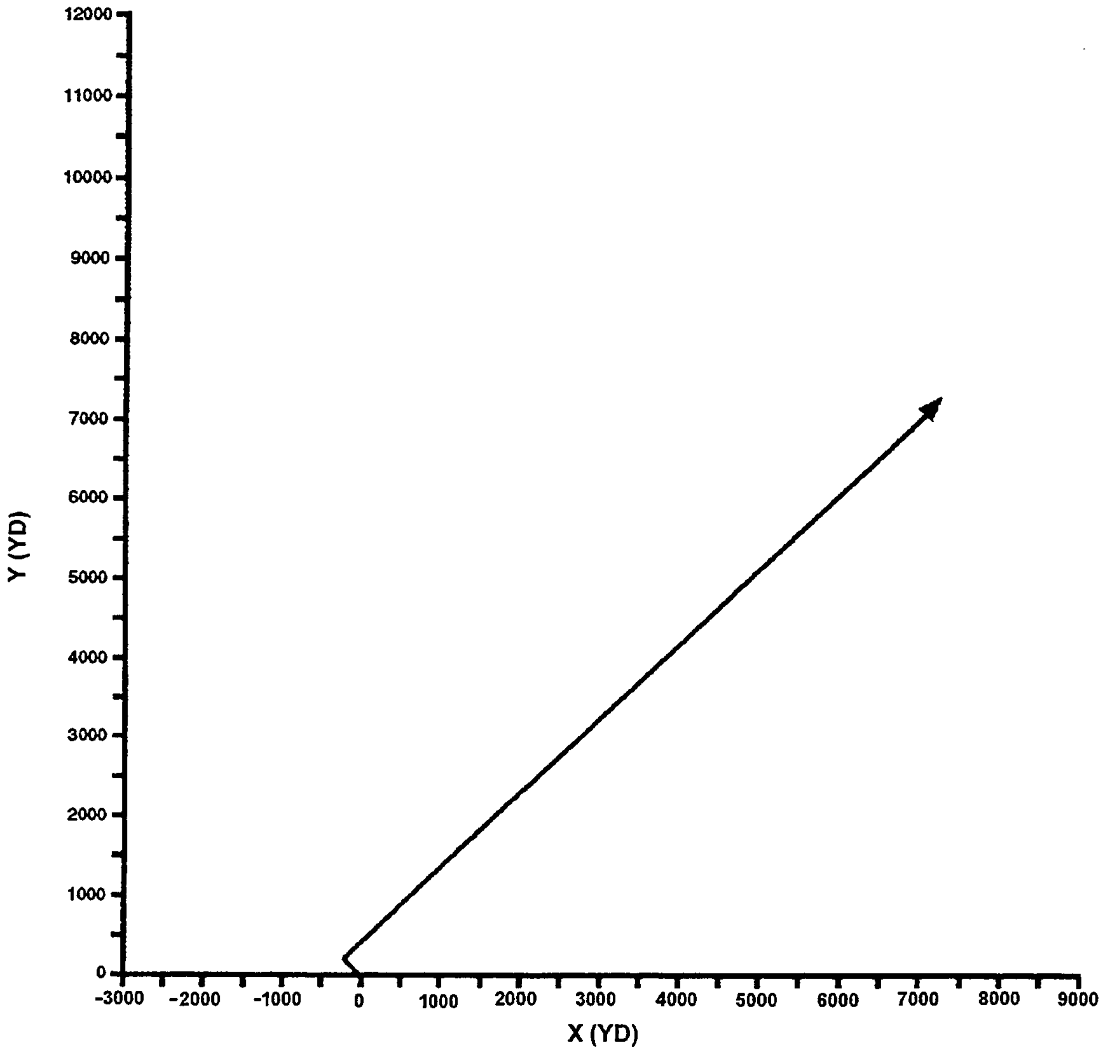


Figure 8. Pursuit Trajectory for Run 2: Approach Angle = 45°, B_c = 45° (Stationary Contact)

Figures 9 and 10 depict the results obtained using the new controller for runs 1 and 2. This controller automatically issued the commands required to direct the vehicle trajectory so that the vehicle arrived at the desired positions at the selected angles of 180° and 135°, respectively.

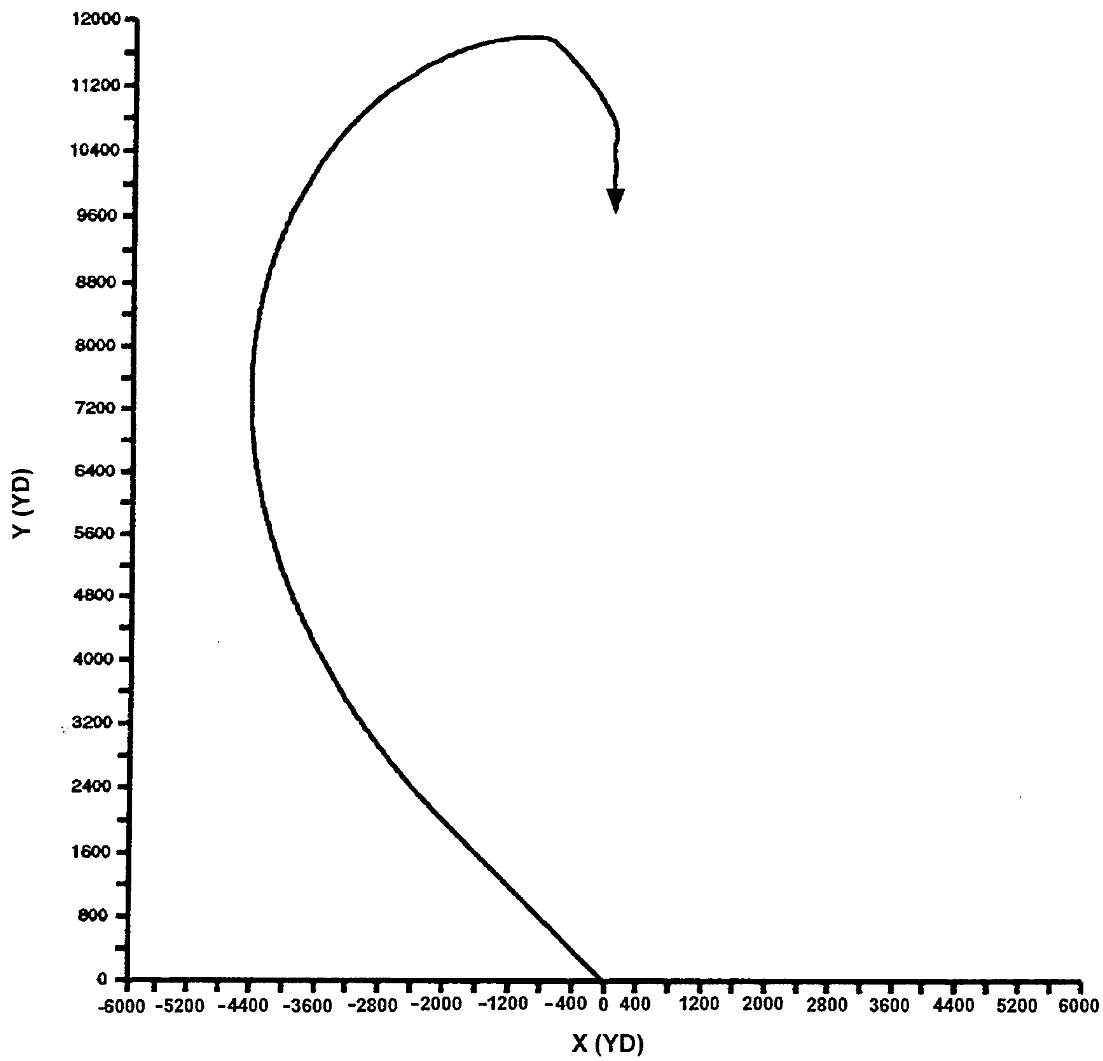


Figure 9. Tail-Chase Trajectory for Run 1: Approach Angle = 180° (Stationary Contact)

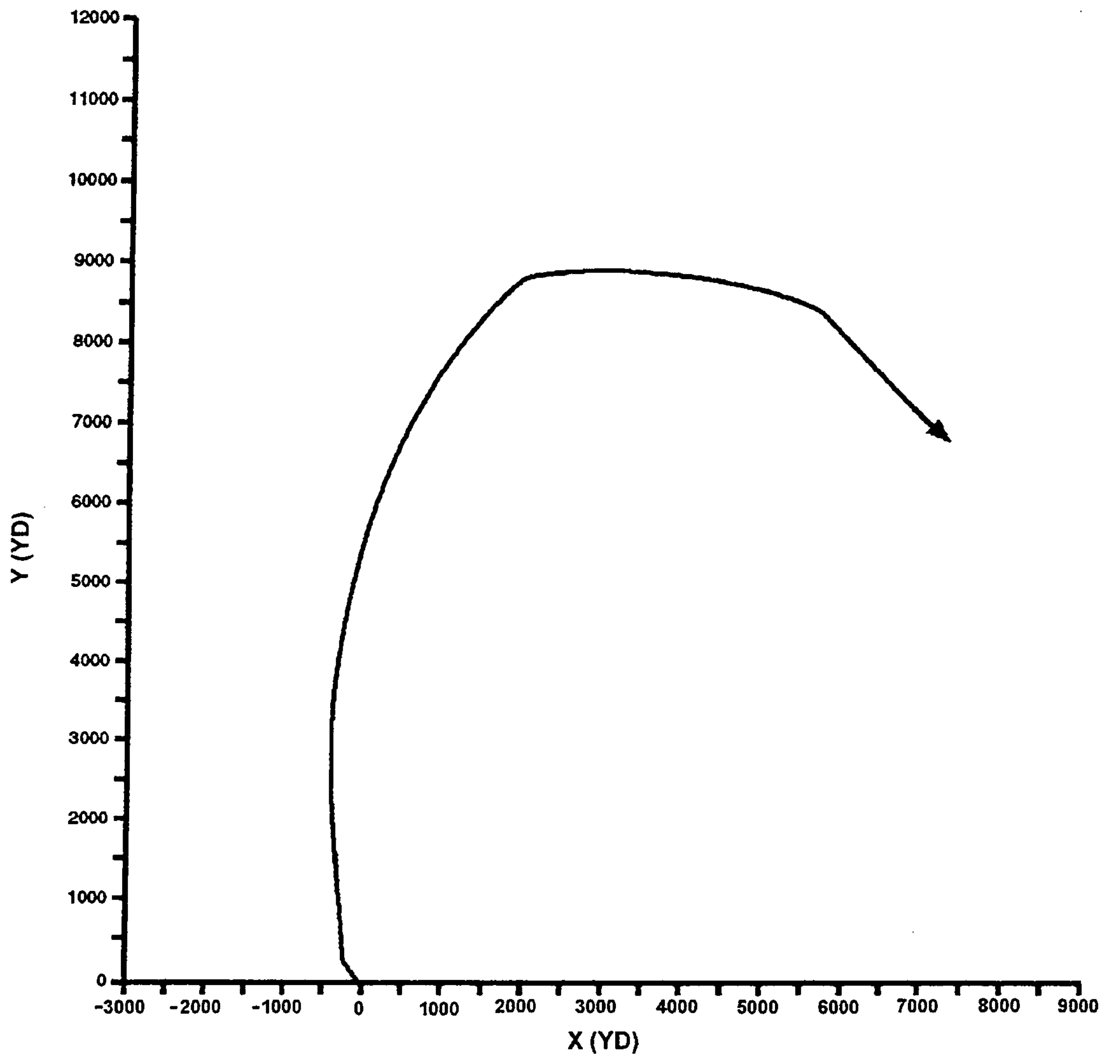


Figure 10. Tail-Chase Trajectory for Run 2: Approach Angle = 135°, B_c = 45° (Stationary Contact)

TAIL CHASE OF A MOVING CONTACT

Figure 11 depicts the geometry for the third sample run. In this scenario, the contact was at a bearing of - 45° with respect to the launching platform, moving at a course of 120°. The pursuing vehicle was launched at an angle of 0°, and the automatic controller was initiated 10 seconds after launch. The vehicle-to-contact speed ratio was 2.

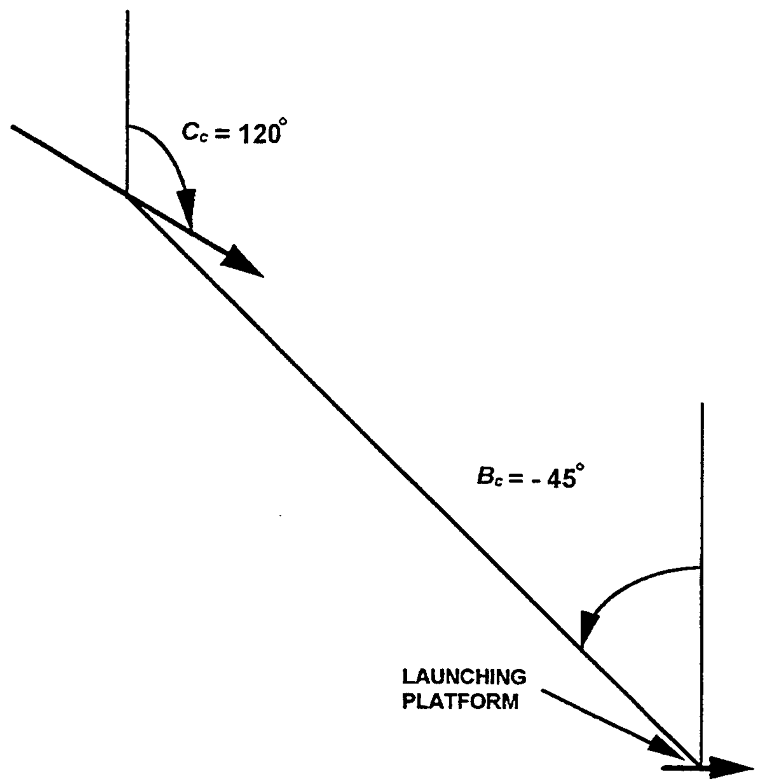


Figure 11. Geometry for Sample Run 3

Figure 12 shows the resulting trajectory when the classical pursuit controller was again employed. Examination of the data associated with this run indicated that the turning rate required of the pursuing vehicle to attain the tail-chase trajectory shown exceeded the capabilities of the vehicle.

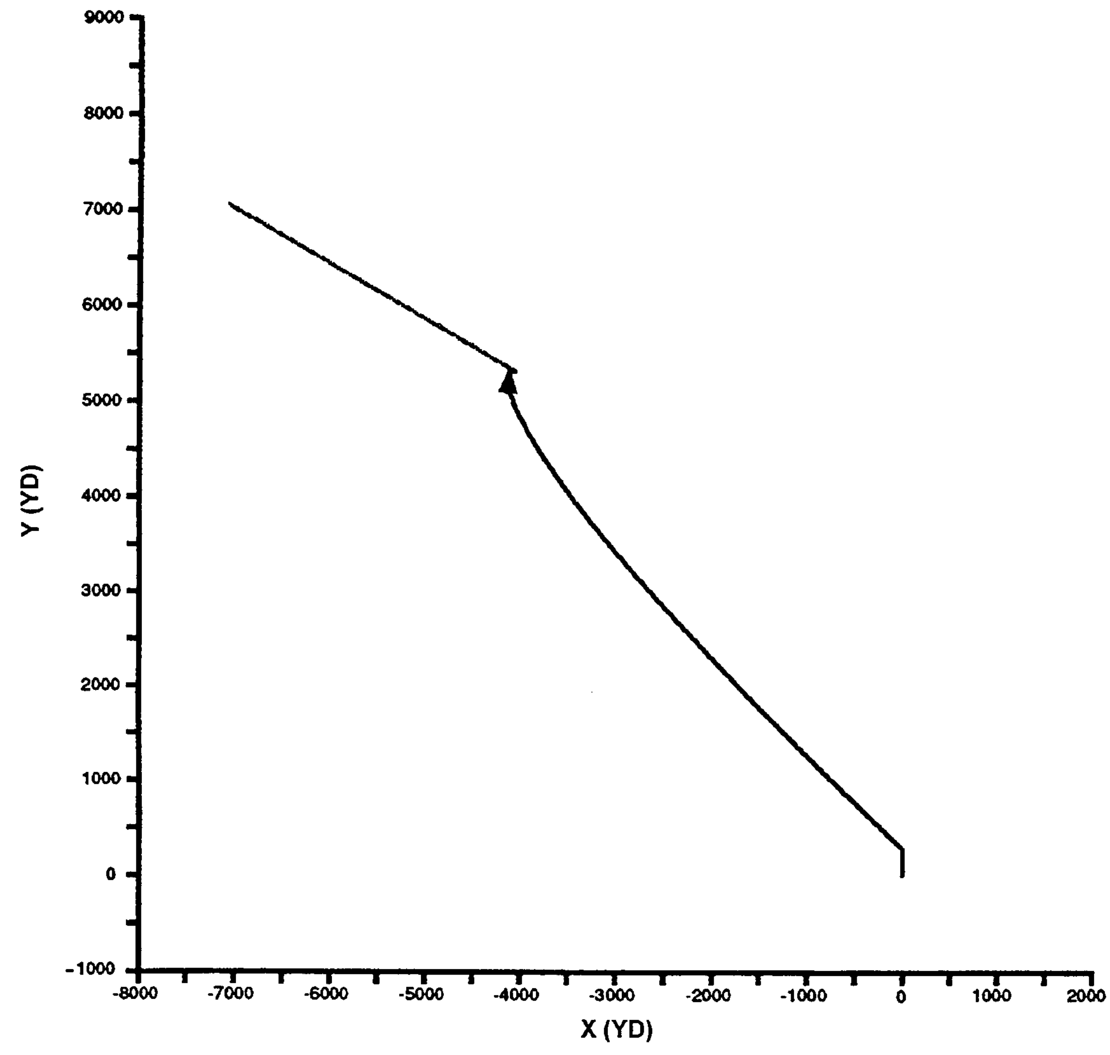


Figure 12. Pursuit Trajectory for Run 3: $C_c = 120°$, $B_c = 45°$, $S_c = 15$ *Knots*

Figure 13 depicts the results obtained using the new controller for run 3. Examination of this trajectory and the associated data indicated no turning rate problem. In addition, this trajectory minimized the problem of the launch platform being unable to continue to track the contact because of the position of the pursuing vehicle with regard to the line of sight.

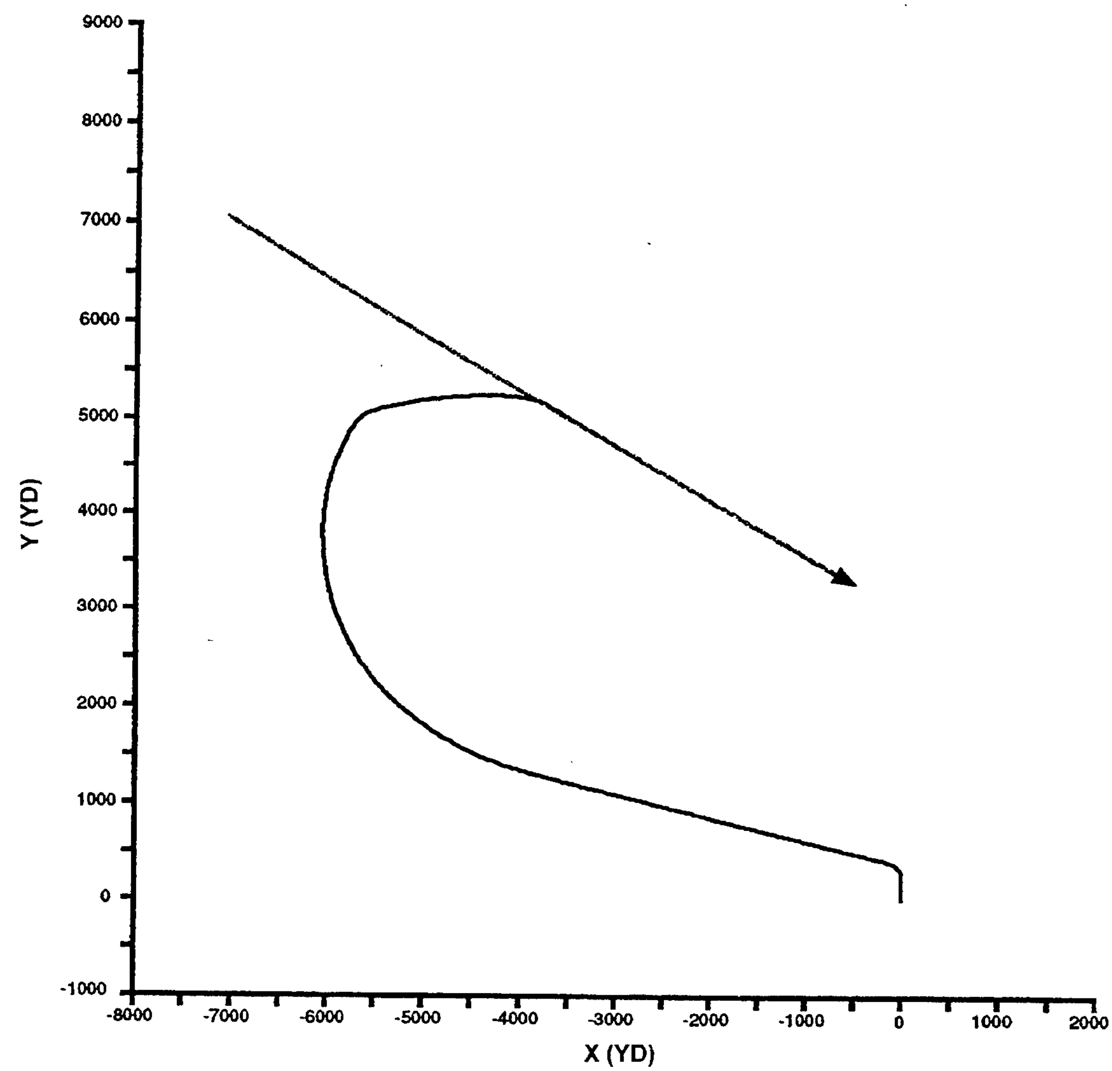


Figure 13. Tail-Chase Trajectory for Run 3: Approach Angle = 120°, B_c = 45°, S_c = 15 Knots

5. SUMMARY AND CONCLUSIONS

The tail-chase controller described in this report is implemented using fuzzy control methodology. Using a new control variable and a heuristic rule set, the tail-chase controller overcomes the limitations of existing control laws. The often prohibitively high turning rates of the classical pursuit controller are no longer required; the approach trajectories are such that the interference of the sensed contact signals by the torpedoes is minimized, allowing more reliable tracking of the contact after the vehicle is launched; and the vehicle approaches the contact at a deceptive angle, potentially decreasing launcher vulnerability.

Test runs of the tail-chase controller using a real-time, high-fidelity laboratory simulation verified the advantages of this new guidance technique for use against both stationary and moving contacts. Trajectories determined with a classical pursuit controller of the type presently used in combat situations were compared with those determined by the new tail-chase methodology for the same target position and arrival angle. The tail-chase controller was more successful in achieving the desired angles of arrival for the stationary contacts. When a moving contact was pursued employing the classical pursuit controller, the turning rate required of the pursuing vehicle to attain the tail-chase trajectory desired exceeded the capabilities of the vehicle. This problem did not occur when the tail-chase controller was employed. In addition, the tail-chase controller provided a trajectory that minimized the problem of the launch platform being unable to track the contact because of the position of the pursuing vehicle with regard to the line of sight.

Because survivability and cost dictate that complex underwater vehicles deployed by SCCSs (e.g., acoustic homing torpedoes) be employed in the most effective manner, the selection of a vehicle trajectory for the postlaunch delivery/search phase is a primary consideration. Use of the newly developed tail-chase controller for weapon trajectory control improves vehicle delivery and can potentially (1) allow the target craft to be disabled using a less lethal weapon, and (2) lessen the probability of vehicle launcher detection. An additional advantage of the tail-chase controller is its ability to deliver a vehicle to a stationary target/position at any desired angle.

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Defense Technical Information Center	2
Defense Advanced Research Projects Agency	1
Center for Naval Analyses	1
Office of Naval Research (ONR-333—J. Fein)	1
Submarine Base Pearl Harbor (Code FB13)	1
Naval Postgraduate School (Code FF42)	1
Naval War College (Code FF44)	1
Naval Air Systems Command (PMO-407)	1
Naval Sea Systems Command (PEO-MIW, ASTO-E, PMS-303, PMS-393, PMO-402, PMO-425)	6
Naval Air Warfare Center Weapons Division, China Lake (P. Kersten (Code 2158))	1
Fleet and Mine Warfare Training Center (Code FT51)	1